COMPOSITE ALUMINUM CONDUCTORS FOR PULSED POWER APPLICATIONS AT HYDROGEN TEMPERATURES

J. C. Ho
Wichita State University
Wichita, KS 67208

C. E. Oberly
Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, OH 45433

and

H. L. Gegel, W. T. O'Hara, J. T. Morgan, Y. V. R. K. Prasad, and W. M. Griffith
Air Force Materials Laboratory
Wright-Patterson Air Force Base, OH 45433

ABSTRACT

The results of a successful feasibility study on fabricating composite aluminum conductors with low electrical resistance at liquid hydrogen temperatures are reported. The conductors contain fine high-purity aluminum filaments embedded in an Al-Fe-Ce alloy matrix. The lightweight, high strength alloy, with favorable thermal and electrical properties, has its workability compatible to that of pure aluminum. Meanwhile, no Fe/Ce diffusion from the matrix to the aluminum filaments occurs during processing.

INTRODUCTION

To meet the ever increasing need for devices generating high power pulses, particularly when weight is of great importance, multifilamentary superconductors have been considered as the most promising materials. Their advantages are based on the practically zero electrical resistance and consequently very large current densities. Nevertheless, producing and maintaining the extremely low temperatures required demand liquid helium with normal boiling point of 4.2K. Peripheral equipment for helium storage and liquefication adds extra complication and weight to the overall operation of a given power system. Moreover, for pulsed power applications, transient heat transfer problems are yet to be resolved. In contrast, this research aims at developing a different kind of cryogenic winding material, which is not superconducting, but has a sufficiently low electrical resistivity at service temperatures near 20K, which are easily attainable whenever liquid hydrogen is available. Specifically, they are composite conductors containing high-purity aluminum filaments embedded in an aluminum-iron-cerium (Al-Fe-Ce) alloy matrix.

MATERIALS REQUIREMENT

High-purity and stress-free aluminum has extremely low electrical resistivity at cryogenic temperatures even under strong magnetic fields [1]. Saturating magnetoresistivity, as well as lightweight, makes aluminum a better choice than copper for the high magnetic field applications under consideration. To allow fast current penetration in pulsed power devices, fine aluminum filaments are required. Their diameters are limited by the size effect of electrical resistivity. Since high-purity aluminum is very soft, the filaments need to be strengthened. This can be most conveniently done by having the filaments embedded in a high strength matrix material. Meanwhile, the matrix should have the following properties: (I) lightweight, (II) high strength, (III) good thermal conductivity, (IV) reasonably high electrical resistivity to minimize eddy current loss and to enhance electromagnetic diffusion rate, (V) workability compatible with that of high purity aluminum, and (VI) diffusionless alloying elements if present. The last requirement is most critical to enabling the high purity of aluminum filaments to persist in the final composite product. It is indeed this requirement which eliminates most known aluminum based alloys from being considered here as a matrix for the high purity filaments.

The breakthrough in this study came about when a new Al-Fe-Ce alloy [2] was tested as the matrix. This lightweight material with favorable thermal and electrical properties was initially developed for high temperature applications. With 8.4 and 3.6 wt.% Fe and Ce, respectively, it derives its strength from densely dispersed fine intermetallic compounds yet to be identified. Al-Fe-Ce ternary compounds are known to exist under equilibrium conditions. However, the alloy used in this effort was powder-metallurgically synthesized by rapid quenching and consequently, its various phases do not necessarily exactly match those formed under equilibrium conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

This feasibility study involves basically extrusion and subsequent analysis of Al-Fe-Ce/pure-Al composites. The study was aimed at demonstrating (i) the compatible workability between the alloy and pure Al, and (ii) the lack of Fe/Ce diffusion from the alloy matrix to the pure Al components. The experimental procedures and results can be summarized as follows:

Initially, nineteen 1/4"-diameter rods of commercially-pure (99.8%) Al were inserted into drilled-through holes in a 2"-diameter x 4"-long Al-Fe-Ce alloy billet (Fig. 1). The billet was previously prepared from powders through cold-compaction followed by vacuum hot pressing (VHP). The composite billet was hot-extruded with a streamlined die [3] to an area reduction of 12:1. Processing parameters (temperature and strain rate) were selected based on dynamic materials modeling [4,5], such that dynamic recrystallization of the alloy matrix would

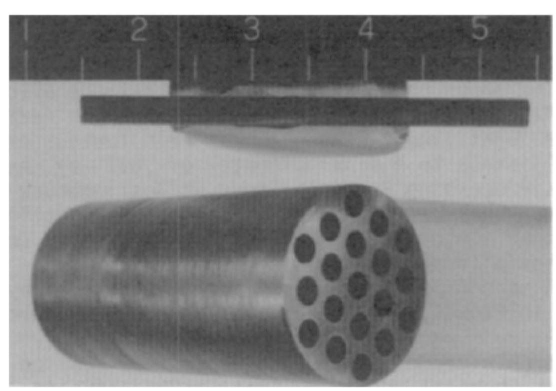

Fig. 1. Starting materials of an Al-Fe-Ce/Al billet.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1985	**N/A**	-

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Composite Aluminum Conductors For Pulsed Power Applications At Hydrogen Temperatures	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Wichita State University Wichita, KS 67208**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT	b ABSTRACT	c THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**3**	

occur. In comparison with the VHP condition, dynamic recrystallization resulted in a product having lower room-temperature yield strength (25 ksi vs. 60 ksi) but much improved microstructure in terms of elimination of prior powder particle boundaries and a more homogeneous intermetallic particle distribution, which then allowed subsequent extrusions to be carried out at lower temperatures. Indeed, this was accomplished by stacking seven sections of the initial extrusion product in a commercially-pure Al ingot and re-extrusion at 12:1. Fig. 2 and Fig. 3 show the 133 Al inserts in Al-Fe-Ce matrix before and after the second extrusion. The cross section geometry is nearly unchanged, and the deformation of Al inserts was reasonably uniform. Micrographs show well defined boundaries between the matrix and the inserts (Fig. 4). The fact that no cracks developed at these interfaces was also encouraging.

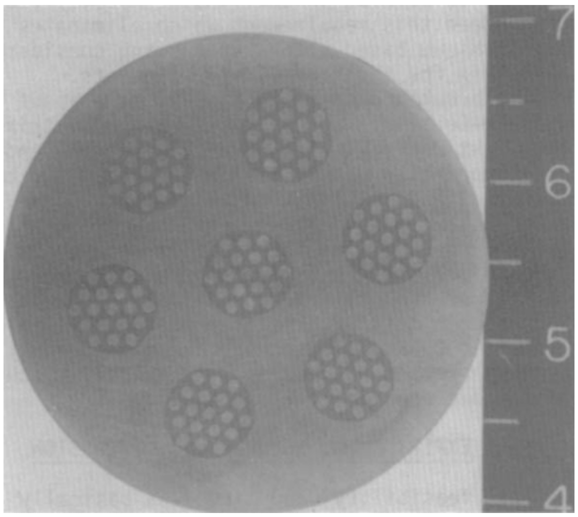


Fig. 2. Stacking of extruded Al-Fe-Ce/Al sections in an Al matrix, ready for a second extrusion.

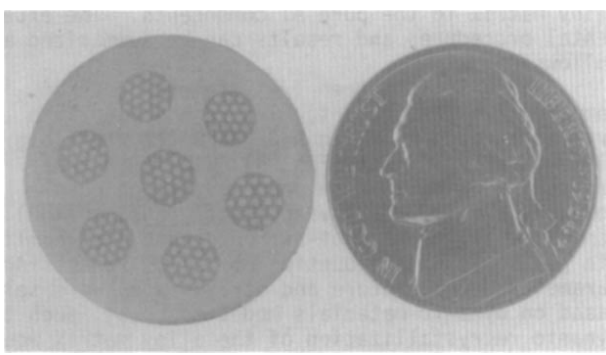
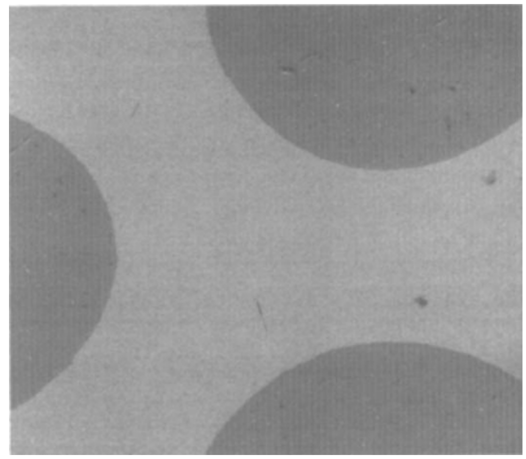


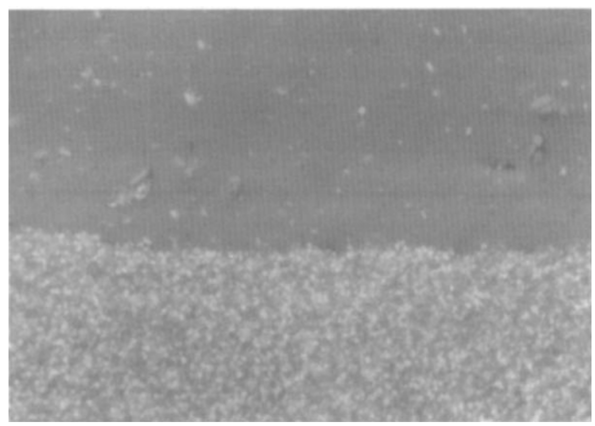
Fig. 3. Cross sections of the re-extruded product with little change in configuration of the 133 filaments as compared to those in Fig. 2.

The above observations suggest that the alloy and pure Al can be coprocessed successfully. In fact, part of the 133-filament composite has been furthur extruded in multisteps to a final diameter of .031" by the Metals Processing Research Group at Westinghouse R & D Center. This represents an overall area reduction of more than 100,000 times for each Al filament. Detailed analyses of results are in progress.

A second billet was prepared in the same way as shown in Fig. 1, except that the nineteen commercially-pure Al rods were replaced by seven high-purity (Puratronic grade, 99.998%) Al rods from Johnson Matthey Chemical, Ltd., so that Fe/Ce diffusion evaluations could be made. Fig. 5 shows the cross section of hot-extruded product with an area reduction of 16 to 1. No detectable Fe or Ce was found in the Al filaments by electron microprobe analysis, setting an upper limit of their concentrations at 100 ppm. Additional verification of this statement was based on residual resistivity ratio (RRR) determinations.



0.01" (250 μm)



0.001" (25 μm)

Fig. 4. Well-defined boundaries between Al filaments and Al-Fe-Ce alloy matrix.

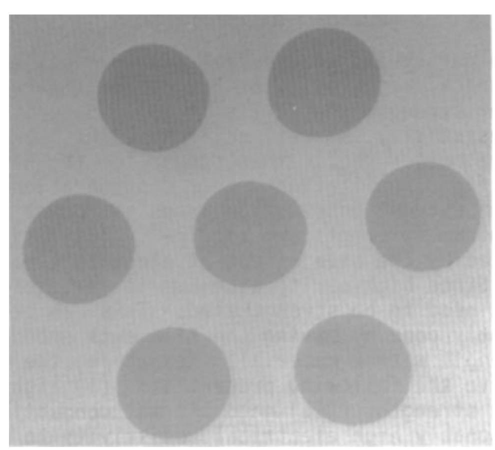


Fig. 5. Cross section of 7 high-purity Al filaments in Al-Fe-Ce matrix, after being extruded to an area reduction of 16 to 1.

An electrical resistivity sample was prepared by machining a 9"-long section of the extrusion product to a 5/16" diameter, with the seven Al filaments comprising 1/4 of the total cross section and the remaining 3/4 being that of the alloy matrix. Using the standard four-probe method, electrical resistivity of the composite rod was obtained following a 2-hour annealing at 200°C:

$$\rho(297K) = 3.5\ \mu\Omega\text{-cm},$$
$$\rho(78K) = 0.40\ \mu\Omega\text{-cm},$$
$$\rho(4.2K) = 0.0088\ \mu\Omega\text{-cm},$$

yielding an RRR value of 400. No change in results was observed after the sample was subjected to a longer (60-hour) annealing at 200°C. The electrical resistivity of the matrix material itself was also measured (RRR = 17). By coupling these values with the relative cross section areas of filaments and matrix (1:3), it was concluded that the RRR value for the Al filaments alone would be close to 900. This is comparable to that of stress-free Al with a 99.99+% purity. At this purity level, the electrical resistivity at liquid hydrogen temperature should be only about twice as high as that at 4.2K.

In summary, the results support the expectation that Fe/Ce diffusion from the matrix during processing is negligible, and the high purity Al filaments maintain their excellent electrical conductivity at low temperatures. It is also reasonable to conclude that internal stress in the filaments induced by the extrusion deformation of the composite is not significant.

REFERENCES

[1] V. D. Arp, M. B. Kasen, and R. P. Reed, Magnet Energy Storage and Cryogenic Aluminum Magnets, Air Force Aero Propulsion Laboratory Technical Report AFAPL-TR-68-87, February 1969.

[2] W. M. Griffith, R. E. Sanders, Jr., and G. J. Hildeman, "Elevated Temperature Aluminum Alloys for Aerospace Applications", in High-Strength Powder Metallurgy Aluminum Alloys, edited by M. J. Koczak and G. J. Hildeman, the Metallurgical Society of AIME, 1982, pp. 209-224; S. D. Kirchoff, R. H. Young, W. M. Griffith, and Y. W. Kim, "Microstructure/Strength/Fatigue Crack Growth Relations in High Temperature P/M Aluminum Alloys", ibid, pp. 237-248.

[3] H. L. Gegel, J. C. Malas, and S. M. Doraivelu, "Process Modeling of P/M Extrusion", in Innovations in Materials Processing, edited by G. Bruggeman and V. Weiss, Plenum Press, New York, NY, 1985, pp. 137-159.

[4] H. L. Gegel, "Material Behavior Modeling - An Overview", in Experimental Verification of Process Models, edited by C. C. Chen, Am. Soc. Metals, Menlo Park, OH, 1983, pp. 3-32.

[5] Y. V. R. K. Prasad, H. L. Gegel, S. M. Doraivelu, J. T. Morgan, K. A. Lark, and D. R. Barker, "Modeling of Dynamic Material Behavior in Hot Deformation: Forging of Ti-6242", Met. Trans. A, Vol. 15, pp. 1883-1892, October, 1984.